Progress Towards Laser Trapping of ^{225}Ra for an Electric Dipole Moment Measurement

N. D. Scielzo[1], I. Ahmad[1], K. Bailey[1], D. L. Bowers[2], J. R. Guest[1], R. J. Holt[1], Z.-T. Lu[1,3], T. P. O'Connor[1], D. H. Potterveld[1], and E. C. Schulte[1]

[1]*Physics Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439*
[2]*Chemical Engineering Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439*
[3]*Department of Physics and the Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637*

Abstract. Many extensions to the Standard Model, such as supersymmetry, predict electric dipole moments (EDMs) just below current experimental sensitivity. In ^{225}Ra, which has an octupole-deformed nucleus, the signature of an EDM is expected to be amplified by two to three orders of magnitude relative to previously studied systems. We plan to collect ^{225}Ra atoms in a magneto-optical trap and transfer the sample to an optical dipole trap where the EDM measurement can be performed. To this end, we have measured the absolute $^1S_0(F{=}1/2)\leftrightarrow{}^3P_1(F{=}3/2)$ transition frequency and determined the lifetime of the lowest $^3P_1$ state in ^{225}Ra. Development of a magneto-optical trap based on this transition is underway.

Keywords: Electric dipole moment, radium.
PACS: 32.70.Cs,32.30.Jc

INTRODUCTION

The discovery of a permanent electric dipole moment (EDM) larger than the extraordinarily small value predicted by the Standard Model would signify a new source of time-reversal violation and CP violation. Extensions to the Standard Model, such as supersymmetry, naturally predict EDMs just below current experimental sensitivity and could also explain the matter-antimatter asymmetry observed in the Universe. In isotopes such as ^{225}Ra ($t_{1/2}$=14.9 days) that have an octupole-deformed nucleus, the signature of an electric dipole moment is expected to be amplified by two to three orders of magnitude relative to previously studied systems [1-5]. We plan to collect ^{225}Ra atoms in a magneto-optical trap (MOT) and then transfer them to an optical dipole trap. From the optical dipole trap, the atoms will be transferred to a magnetically-shielded measurement chamber and spin polarized by optical pumping. The electric dipole moment can then be determined from the precession frequency in the presence of carefully controlled electric and magnetic fields.

Detailed knowledge of the transition frequencies and lifetimes of low-lying states is needed to laser cool and trap ^{225}Ra atoms. Until now, the best measurements of the energy of the atomic levels were spectroscopic studies of the longest-lived radium isotope (^{226}Ra, $t_{1/2}$=1600 years) performed in 1934 [6,7] and no lifetimes have been measured. Several calculations of atomic lifetimes, branching ratios, and transition rates have been performed [8-11]. Experimental data is lacking to constrain the calculations and predictions of the $^3P_1$ state lifetime vary from 250-505 ns [8-11]. By probing atoms in a thermal atomic beam, we have measured the $^1S_0(F=1/2)\leftrightarrow{}^3P_1(F=3/2)$ transition frequency and determined the lifetime of the lowest $^3P_1$ state in preparation for developing a MOT based on this transition [12].

EXPERIMENTAL APPARATUS

We chemically separated ^{225}Ra from a 250-μCi source of the long-lived parent nuclide ^{229}Th ($t_{1/2}$=7300 years) and the solution was dried in a titanium crucible. We added 100 mg of barium metal to aid in the reduction of the radium and passivation of the crucible surfaces. At temperatures above 650 ^{0}C, neutral atomic beams of barium (>10^9 atoms/sec) and radium (>10^6 atoms/sec) emerged from the crucible.

The intercombination transition of radium at 714.3 nm was excited using light from a Ti:sapphire ring laser pumped by a frequency-doubled, diode-pumped Nd:YVO_4 laser. The laser beam could be directed either perpendicular to or antiparallel to the atomic beam. The laser linewidth was broadened to approximately 20 MHz to match the transverse Doppler spread of the diverging atomic beam by double-passing through an acousto-optic modulator (AOM) operated with a radio-frequency (RF) carrier mixed with white noise. The laser light was shuttered by switching off the RF signal applied to this AOM. A simple lens system focused 5% of the scattered light from the atoms onto a photomultiplier tube (PMT) with 10% quantum efficiency. A filter with bandwidth of 4 nm reduced backgrounds from the crucible and heating elements to several kHz.

RESULTS

For the measurements of the $^1S_0(F=1/2)\leftrightarrow{}^3P_1(F=3/2)$ transition frequency in ^{225}Ra, the laser frequency was locked to a hyperfine transition of molecular I_2 at

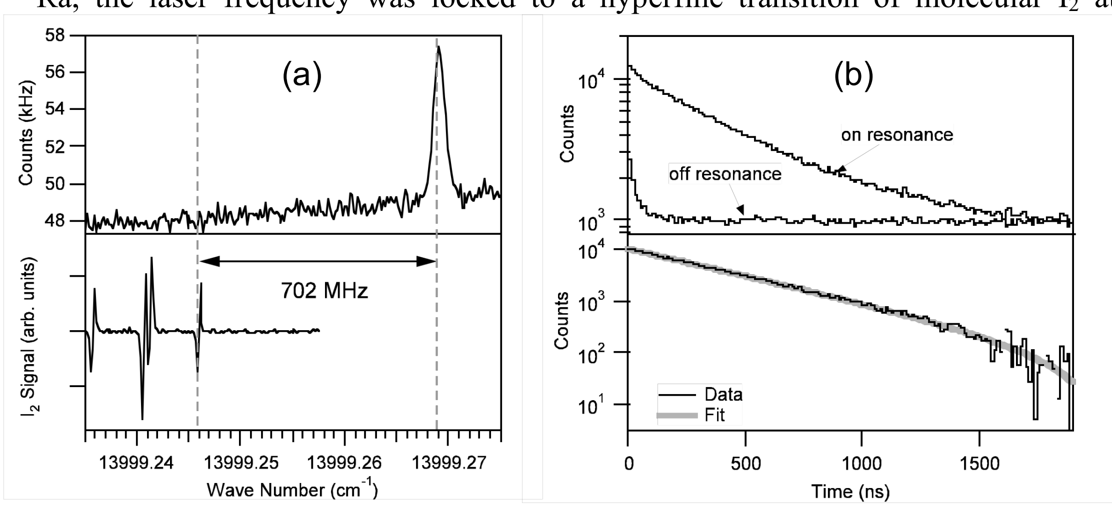

FIGURE 1. (a) Fluorescence detected from the $^1S_0(F=1/2)\leftrightarrow{}^3P_1(F=3/2)$ transition in ^{225}Ra and nearby I_2 transitions. (b) Typical distribution of photon arrival times after shuttering the laser and a fit to background-subtracted data.

13999.2459±0.0005 cm^{-1} [13] shown in Fig. 1(a) using optical heterodyne saturation spectroscopy [14]. We determined the transition to be at 13999.269±0.001 cm^{-1} by scanning the laser frequency and locating the peak of the fluorescence relative to the I_2 transition. From these results, the $^1S_0 \leftrightarrow {}^3P_1$ transitions for ^{212}Ra and $^{222-226}$Ra were also determined to the same precision after correcting for the measured isotope shifts [15]. We infer a value of 13999.357±0.001 cm^{-1} for ^{226}Ra which is 700 MHz lower than the previous measurement [6].

The $^3P_1$ lifetime was determined by observing the exponential decay of fluorescence detected at the PMT for approximately five lifetimes after shuttering the laser beam. We subtracted the background (measured by detuning the laser by several GHz) from the data before performing a least-squares fit to a single exponential and uniform offset. Figure 1(b) shows the fit to the data for typical ^{225}Ra measurements. Systematic effects were thoroughly investigated using ^{138}Ba, for which data could be rapidly accumulated with the laser beam directed either transverse to or anti-parallel to the atomic beam. No statistically systematic significant shifts were uncovered by varying experimental conditions such as the laser beam direction, diameter, and pointing, as well as the cycle rate. The ^{225}Ra measurements, each conducted under a different set of experimental conditions, all fall in the ranges 422±20 ns which we conservatively take as the 1σ total uncertainty. Development of a magneto-optical trap for ^{225}Ra based on this transition is currently underway.

ACKNOWLEDGMENTS

We thank H. A. Gould of Lawrence Berkeley National Laboratory for the generous loan of a ^{229}Th source. This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. W-31-109-ENG-38.

REFERENCES

1. V. Spevak and N. Auerbach, *Phys. Lett. B* **359**, 254 (1995).
2. V. Spevak, N. Auerbach, and V. V. Flambaum, *Phys. Rev. C* **56**, 1357 (1997).
3. J. Engel, J. L. Friar, and A. C. Hayes, *Phys. Rev. C* **61**, 035502 (2000).
4. J. Dobaczewski and J. Engel, *Phys. Rev. Lett.* **94**, 232502 (2005).
5. J.S.M. Ginges, V.V. Flambaum, Phys.Rept.397:63-154,2004.
6. E. Rasmussen, *Z. Phys*. **86**, 1934 (1934).
7. H. N. Russell, *Phys. Rev.* **46**, 989 (1934).
8. V. A. Dzuba, V. V. Flambaum, and J. S. M. Ginges, *Phys. Rev. A* **61**, 062509 (2000).
9. P. Hafner and W. H. E. Schwarz, *J. Phys. B* **11**, 2975 (1978).
10. J. Bruneau, *J. Phys. B* **17**, 3009 (1984).
11. V. A. Dzuba and J. S. M. Ginges, arXiv:physics/0511199 (2005).
12. N. D. Scielzo, *et. al*., to be published in *Phys. Rev. A* (2006).
13. H. Knockel, B. Bodermann, and E. Tiemann, *Eur. Phys. J. D* **28**, 199 (2004).
14. J. L. Hall, L. Hollberg, T. Baer, and H. G. Robinson, *Appl. Phys. Lett*. **39**, 680 (1981).
15. K. Wendt, S. A. Ahmad, W. Klempt, R. Neugart, E. W. Otten, and H. H. Stoke, *Z. Phys. D* **4**, 227 (1987).